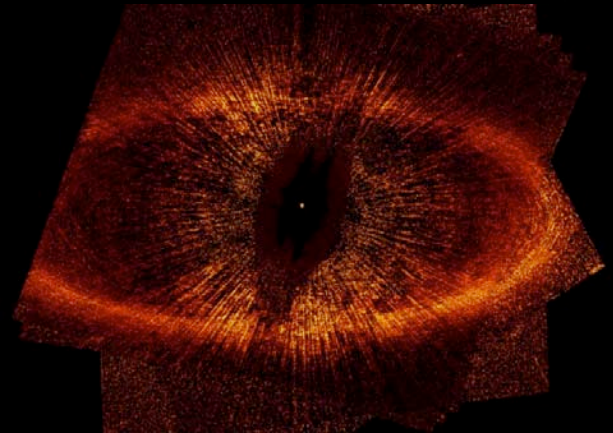
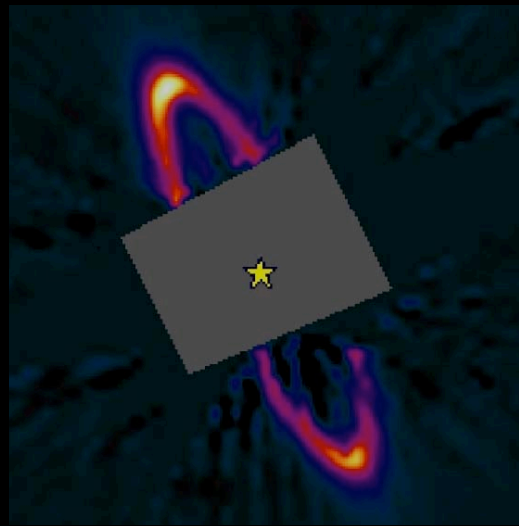
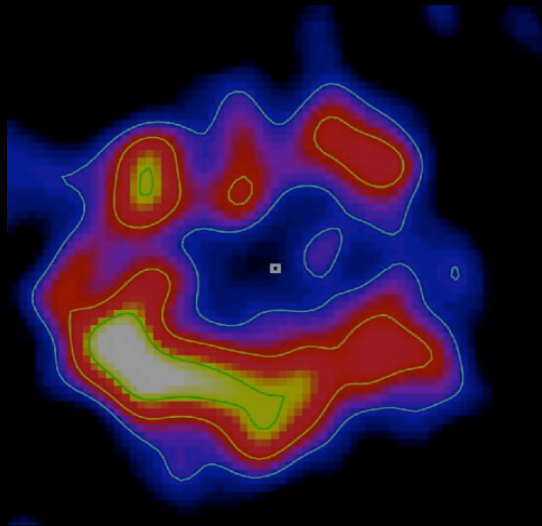


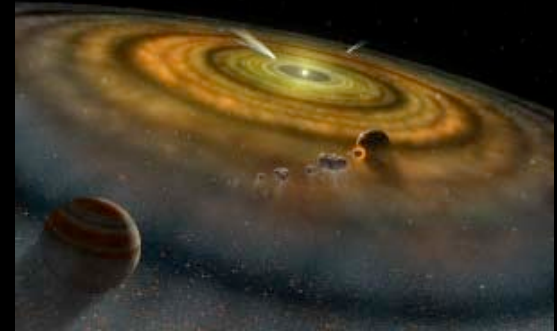
Gas and Dust in Debris Disks

Clues to the Late Stages of Planetary System Formation

Dr. Aki Roberge (NASA GSFC)



Outline

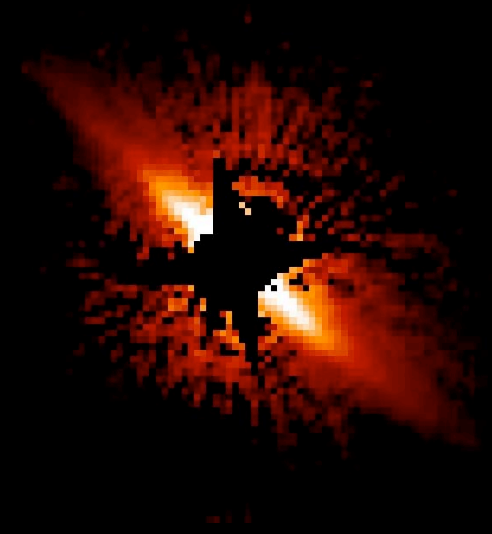


1. Introduction

2. Primordial Gas in Debris Disks?

3. Secondary Gas in Debris Disks

4. Dust in Debris Disks



5. Debris Disks and Extrasolar Terrestrial Planets

Theoretical & Observational Timelines

Theory

Gas giant
planets
form

Terrestrial
planets
form

Disk
clearing



Star
formation



Time (millions of years)

1

5

10

1 Gyr

Planetary
system

Primordial
disk



Transitional
disk



Debris
disk



Observation

Disk Evolution

$10 - 100 M_{\text{Jupiter}}$ $\text{few } M_{\text{Lunar}} \text{ (dust)}$

Total Mass

$10 - 100 M_{\text{Jupiter}}$?

Gas Mass

Time (millions of years)

1

5

10

1 Gyr

Primordial
disk



Transitional
disk



Debris
disk

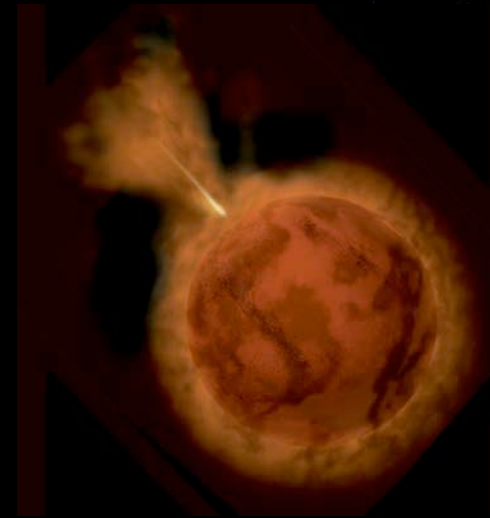


Observation

Debris Disks

- Wide range of ages :
~ 10 Myr to ~ 1 Gyr
- Optically thin disks
 - Short dust lifetimes
- Secondary material (not primordial)
- Delivery of **volatiles** to terrestrial planet surfaces
(e.g. Morbidelli et al. 2000)

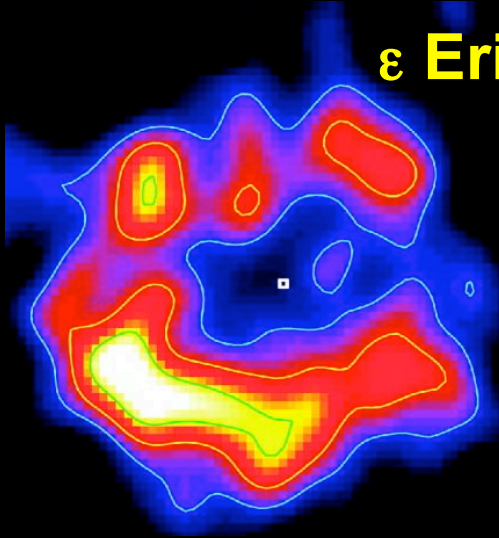
AU Mic — 12 Myr
Krist et al. (2004)



Dust Structures

Clumps

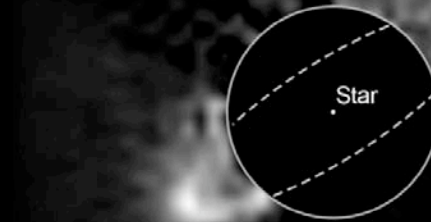
ϵ Eridani @ 850 μm



Greaves et al. (2005)

Rings

HR 4796 w/ NICMOS



Schneider et al. (1999)

Caused by
unseen
planets ?

Warps

β Pictoris w/ ACS



Golimowski et al. (2006)

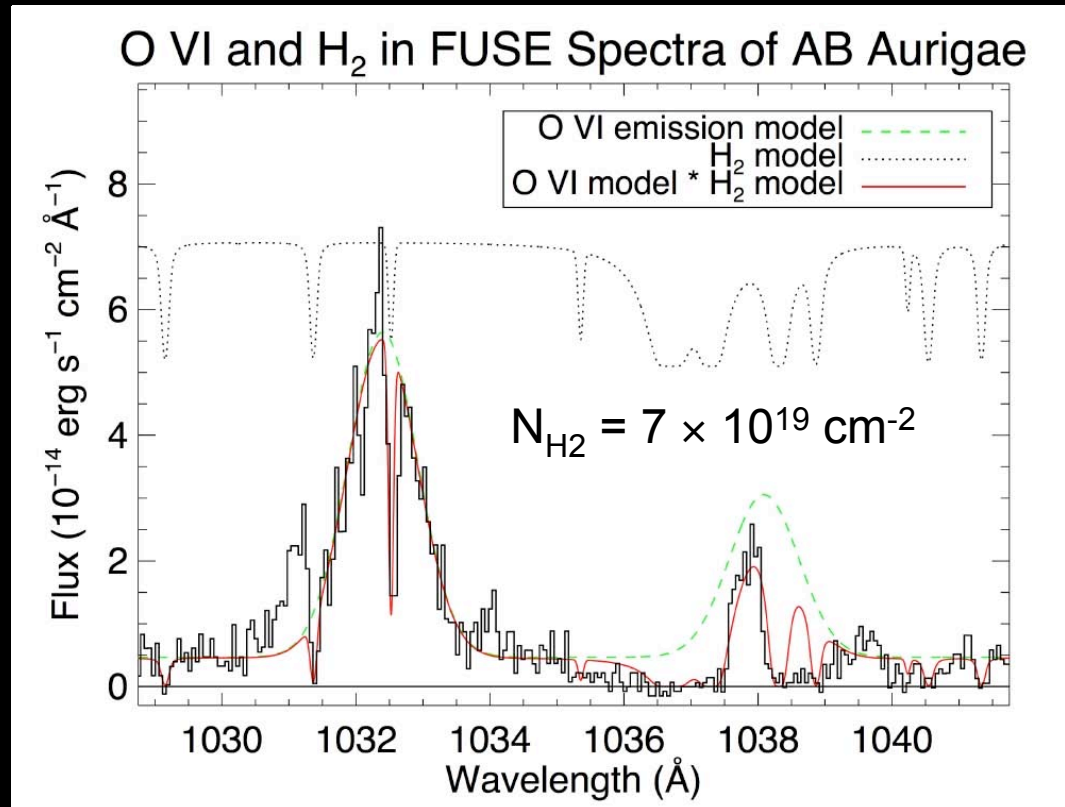
Primordial Gas in Debris Disks?

- Lifetime of primordial gas limits the timescale for giant planet formation, controls planet migration
- Only one detection of sub-mm CO emission in a debris disk (49 Ceti ; Dent et al. 2005)
 - Gas giant planet formation no longer possible
- But ... CO depletion relative to H_2 ?
 - Claimed ISO detection of mid-IR pure rotational H_2 emission from Beta Pic, HD 135344, and 49 Cet (Thi et al. 2001)



FUSE Spectra of H₂

- Far-UV H₂ :
 - Dipole-allowed transitions
 - Sensitive to cold gas
 - No CO/H₂ ratio needed
- But faint stellar FUV continua

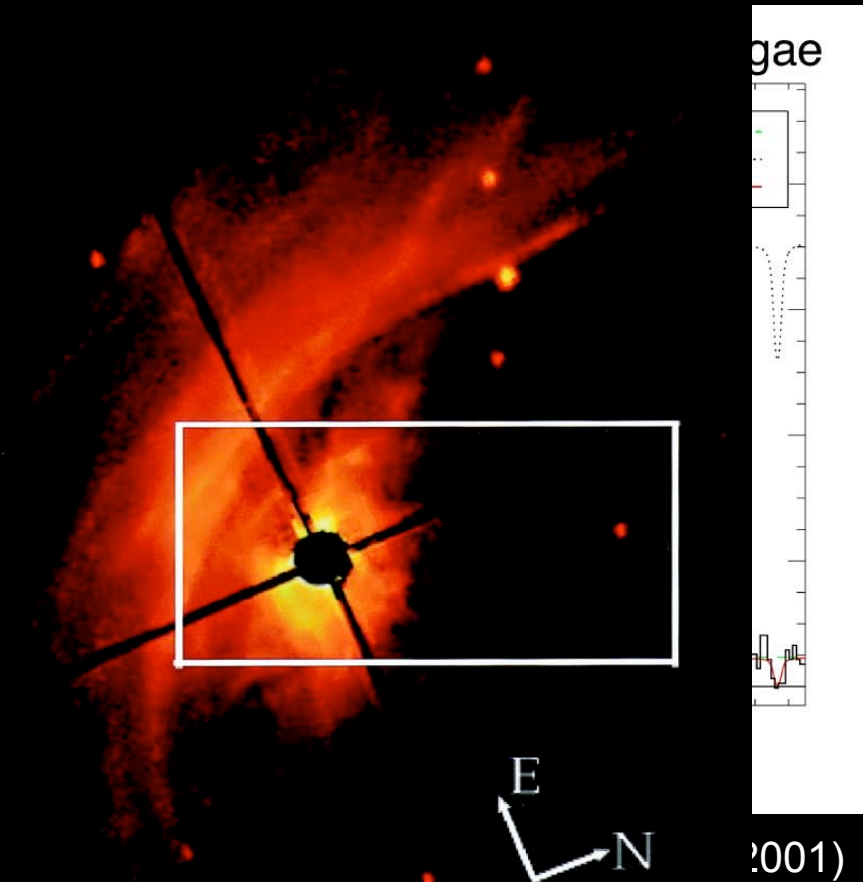
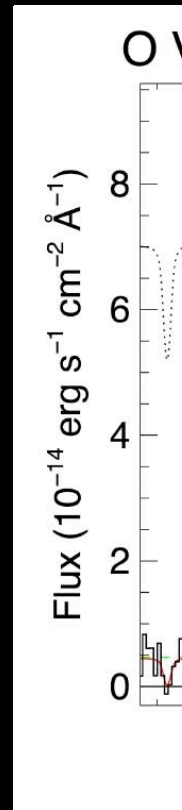


Roberge et al. (2001)

- H₂ lines overlap with emission lines
- Can provide background flux for H₂ absorption

FUSE Spectra of H₂

- Far-UV H₂ :
 - Dipole-allowed transitions
 - Sensitive to cold gas
 - No CO/H₂ ratio needed
- But faint stellar FUV continua
- H₂ lines overlap with emission
- Can provide background flux



AB Aur — 2 Myr old

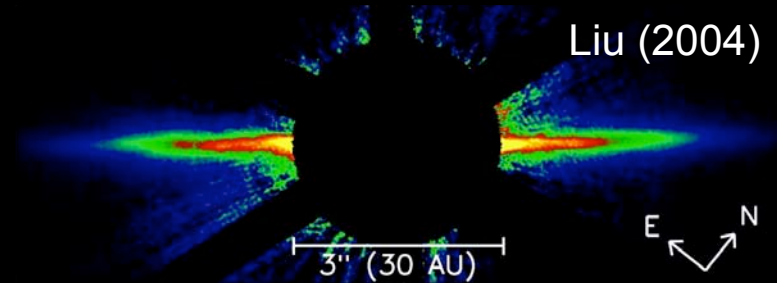
Grady et al. (1999)

Limits on H_2 in Debris Disks

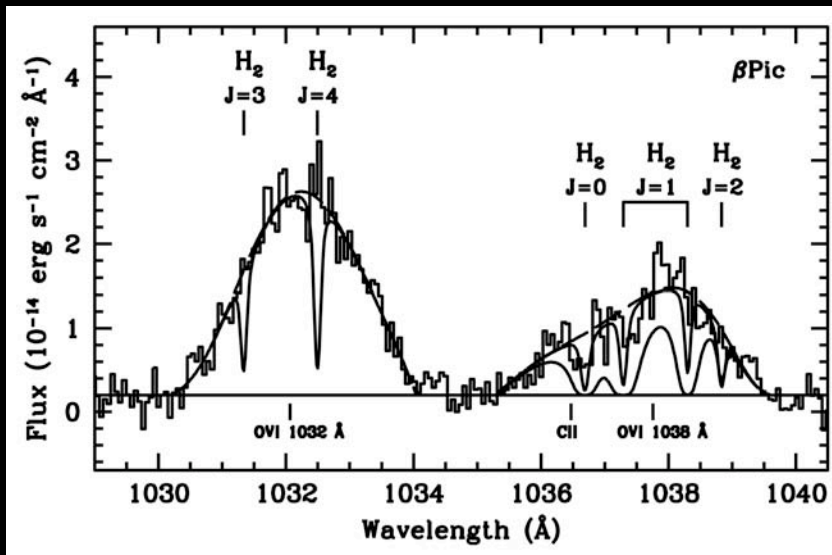


Golimowski et al. (2006)

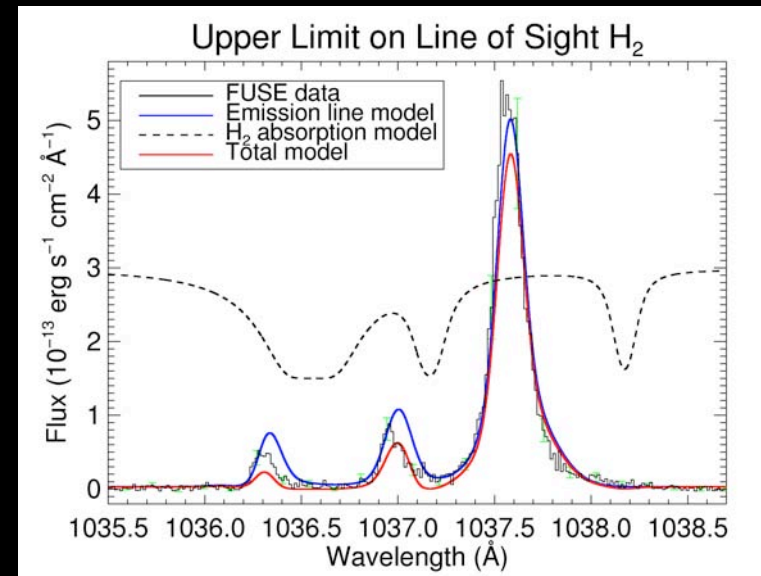
Beta Pic – 12 Myr old A5V



AU Mic – 12 Myr old M1



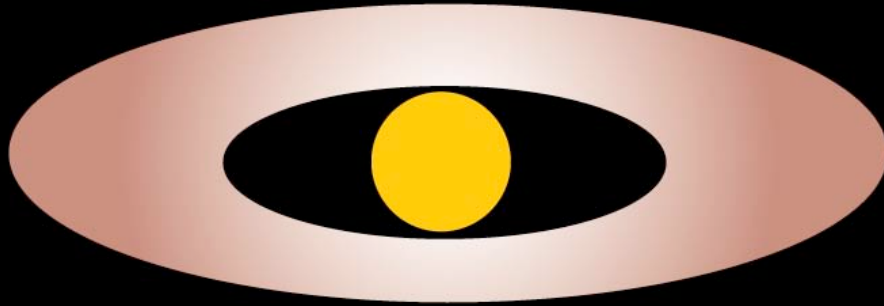
Lecavelier des Etangs et al. (2001)



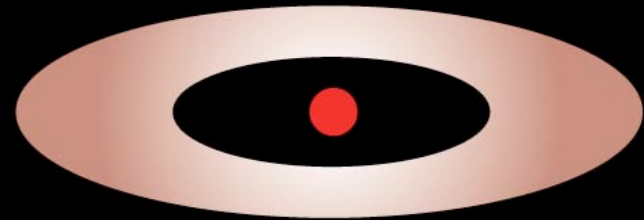
Roberge et al. (2005)

Beta Pic vs. AU Mic

$$M_{\text{H}_2} < 0.12 M_{\oplus}$$



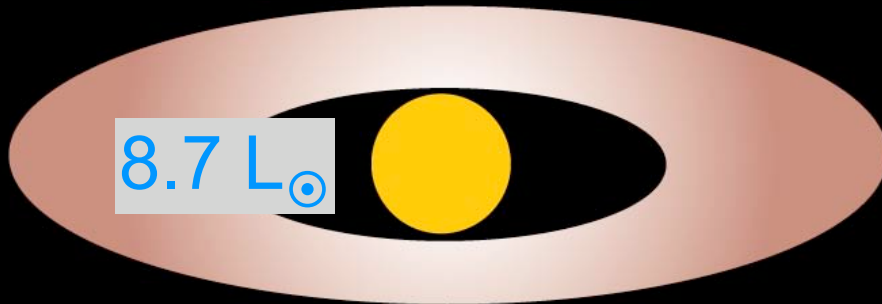
$$M_{\text{H}_2} < 0.06 M_{\oplus}$$



No more giant planet formation

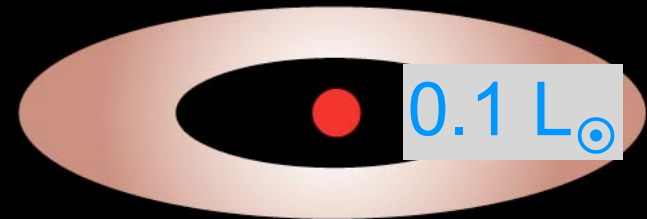
Beta Pic vs. AU Mic

$$M_{\text{H}_2} < 0.12 M_{\oplus}$$

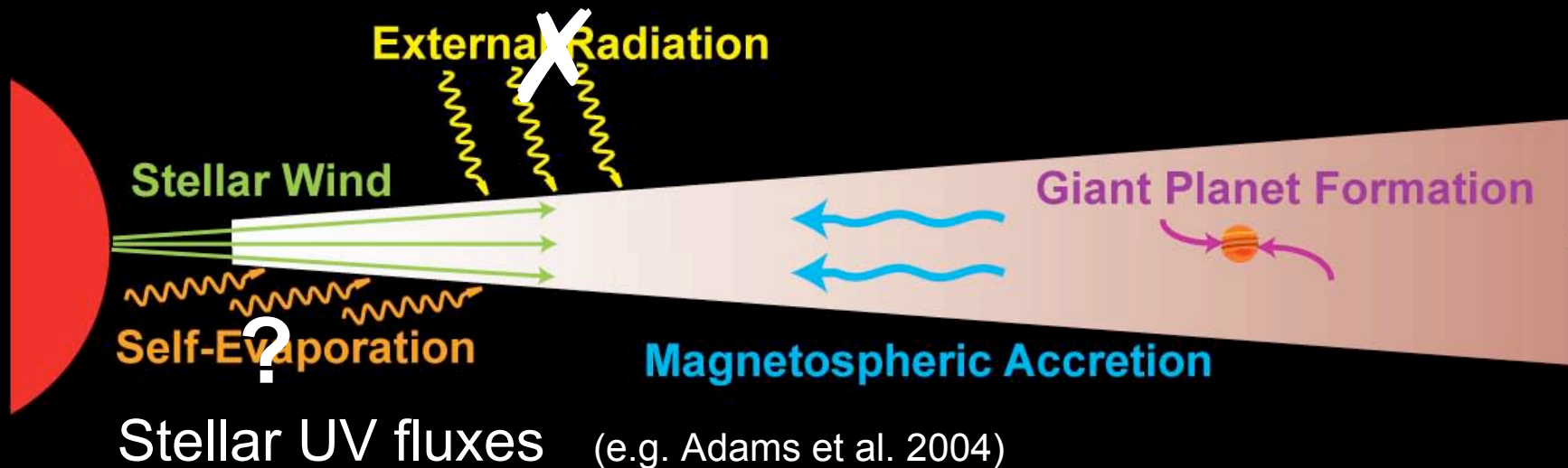


$$M_{\text{H}_2} / M_{\text{dust}} < 3:1$$

$$M_{\text{H}_2} < 0.06 M_{\oplus}$$



$$M_{\text{H}_2} / M_{\text{dust}} < 6:1$$



Upcoming Primordial Gas Studies

- Large dispersion in estimates of gas lifetimes
 - Between ~ 10 Myr and < 1 Myr (Hillenbrand 2005)
- H_2 emission weak, sub-mm CO emission often saturated or undetectable

Upcoming Primordial Gas Studies

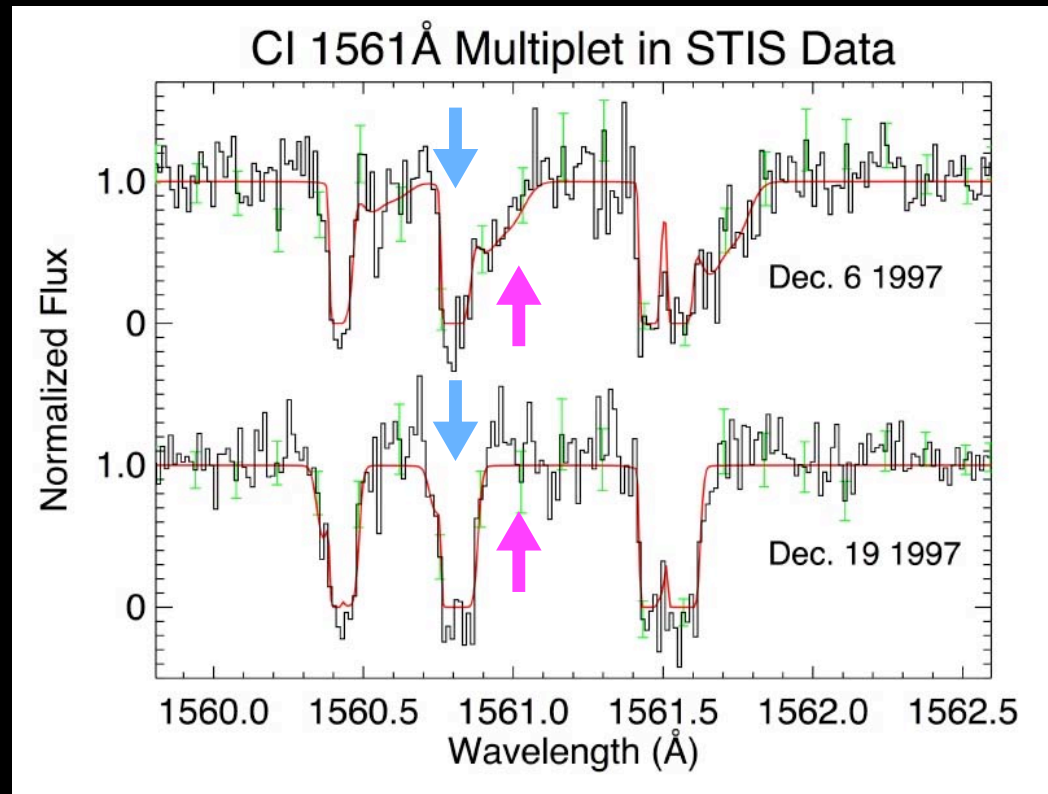
- Herschel Space Observatory
 - Far-IR to sub-mm imaging and spectroscopy
- Open Time Key Projects
 - “Gas in Protoplanetary Systems” (GASPS)
PI: W. Dent (UKATC, Edinburgh)
 - “Dust Around Nearby Stars” (DUNES)
PI: C. Eiroa (UAM, Madrid)



<http://herschel.esac.esa.int/>

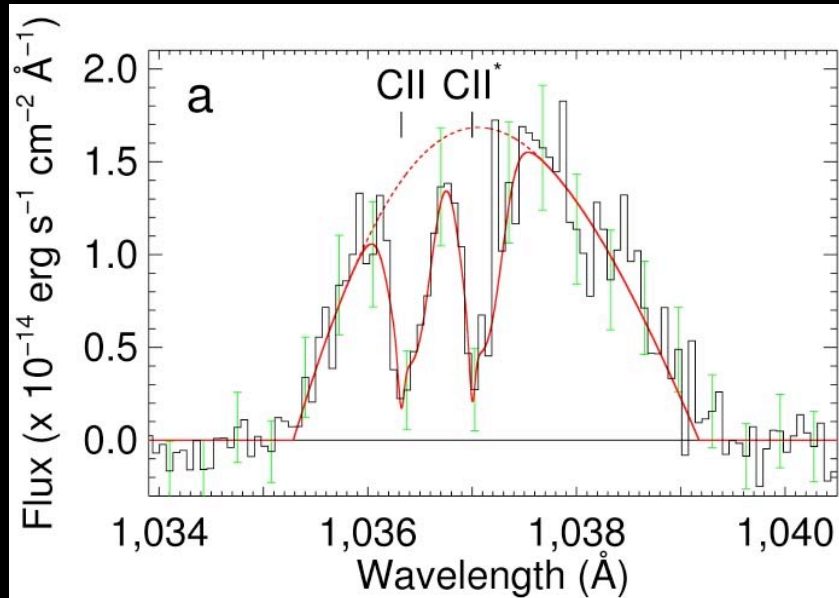
Secondary Gas in Debris Disks

- Abs. lines in Beta Pic spectra from circumstellar gas
- Narrow unvarying features at $v = v_{\star}$: stable gas
- Variable redshifted features :
vaporization of star-grazing planetesimals (FEBs)

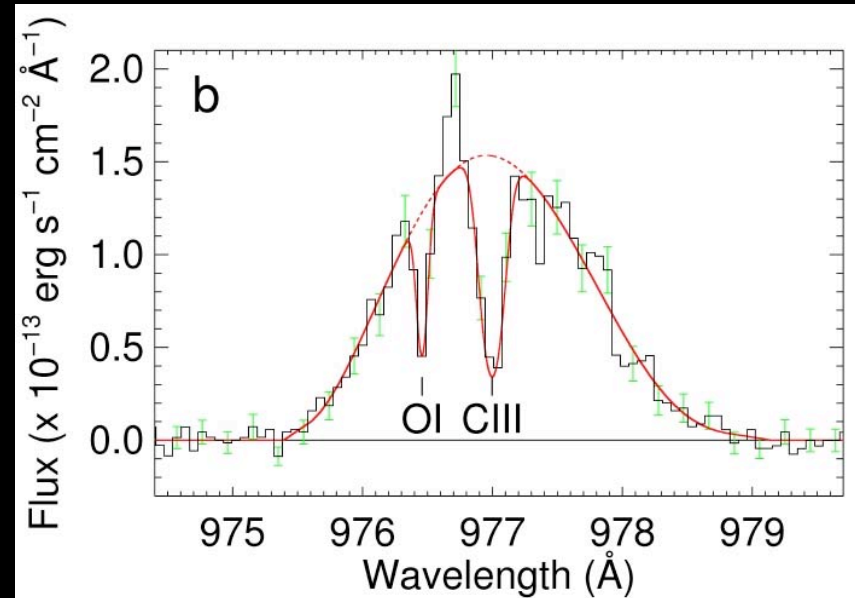


Roberge et al. (2000)

CII and OI in the Stable Gas



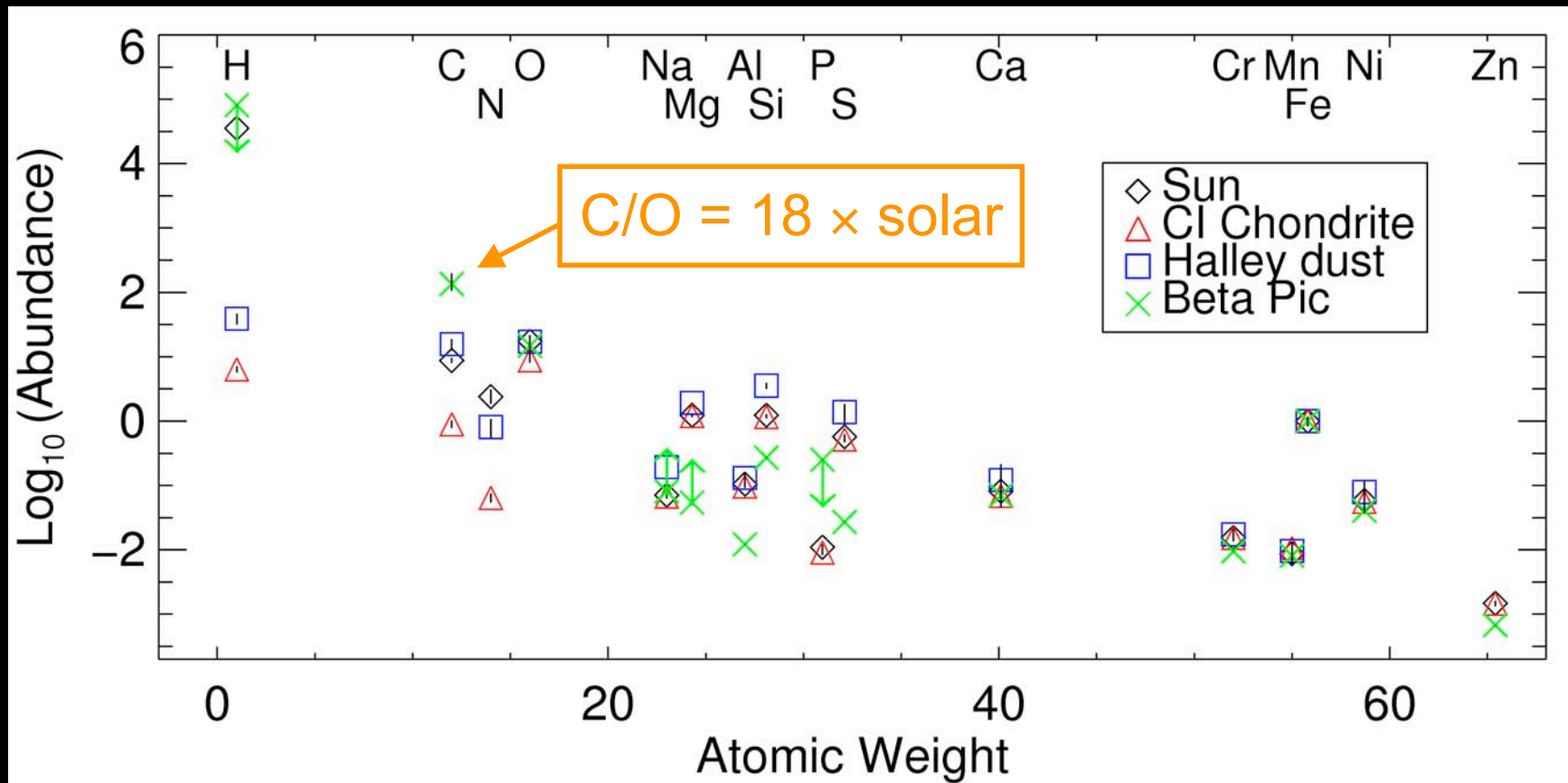
Roberge et al. (2006)



Roberge et al. (2006)

- Inventory of two volatile elements
- Previous measurements primarily metallic species, showed solar composition (like star)

Beta Pic Gas Composition

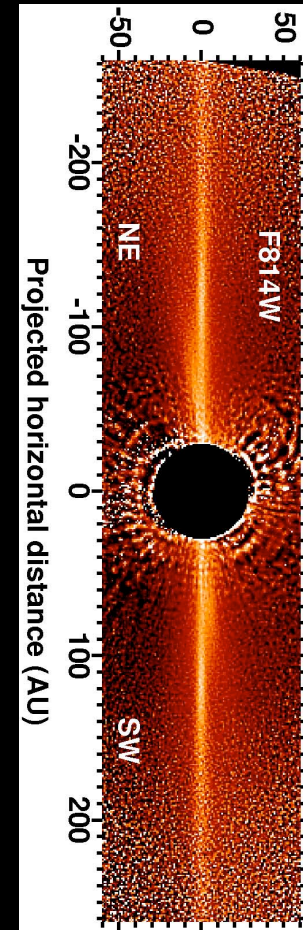


Roberge et al. (2006)

C-rich AGB stars: $\text{C/O} < 1.2$
(Mattsson et al. 2007)

Dynamics of the Gas

- Radiation pressure →
blow away stable gas
(e.g. Lagrange et al. 1998)
- Need unseen braking gas

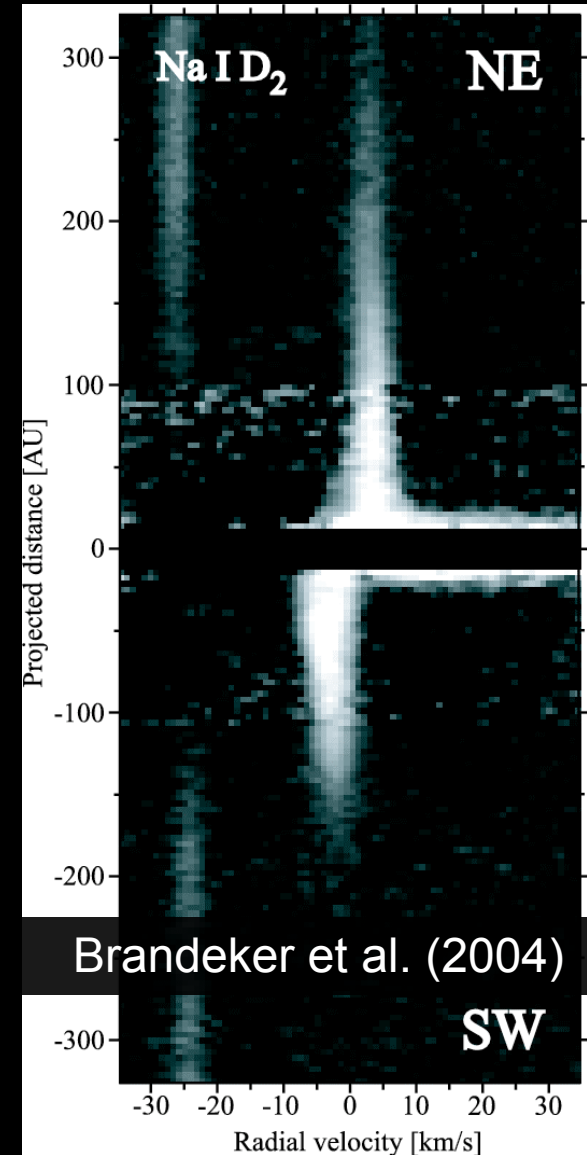


Golimowski et al. (2006)

Dynamics of the Gas

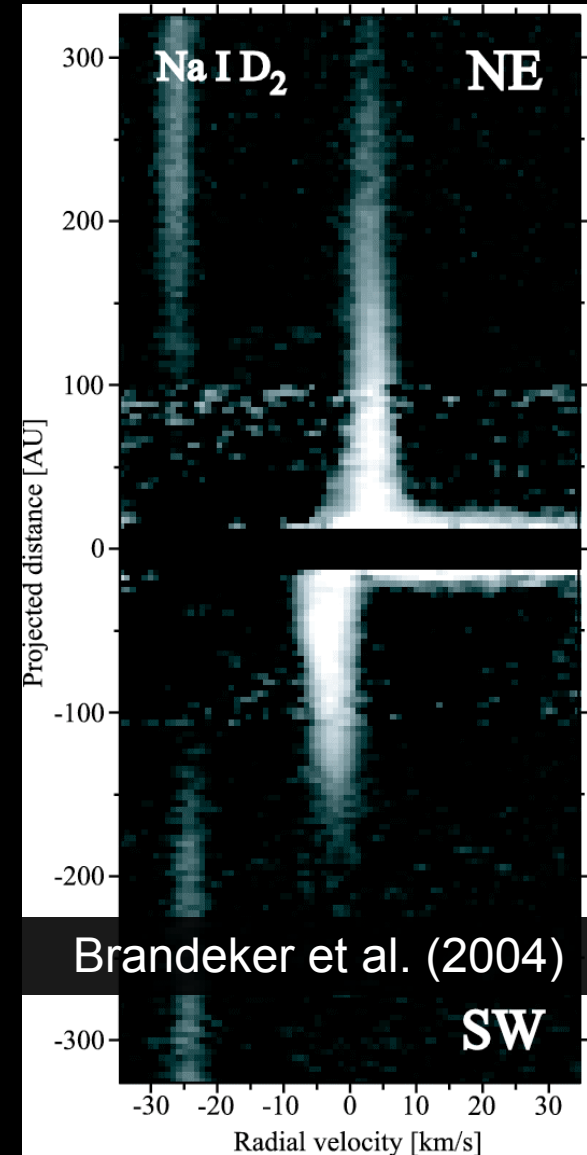
- Radiation pressure → blow away stable gas (e.g. Lagrange et al. 1998)
- Need unseen braking gas
- Image in resonantly scattered Na I emission (Olofsson, Brandeker, & Liseau 2001)

β Pic gas disk in Keplerian rotation out to 100s of AU



Dynamics of the Gas cont'd

- Modeling of Coulomb forces
(Fernandez, Brandeker, & Wu 2006)
 - Ions couple into single fluid
with effective β -value
 - If solar abundance, still need
unseen braking gas
- C is important in ionic fluid
 - If $C \geq 10 \times$ solar,
gas will self-brake

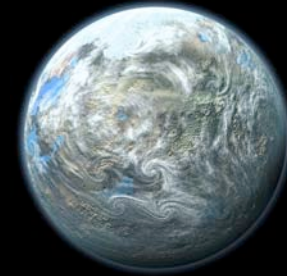


Why is the Gas C-Rich?

- Carbon-rich planetesimals

- $O > C$, left-over O makes water
- $O < C$, left-over C makes methane, graphite, etc.

Earth-like

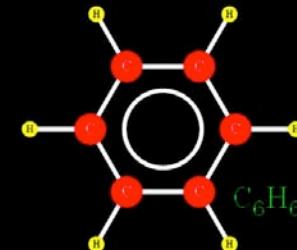


Titan-like



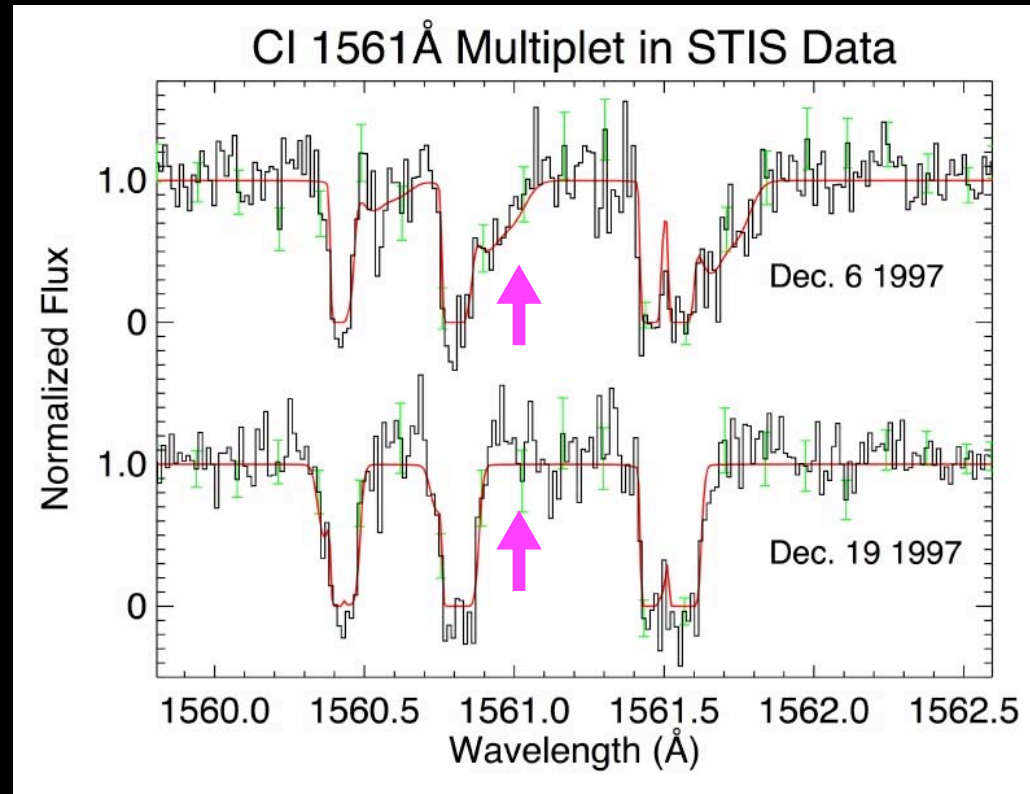
- Evaporation of volatile carbon material

- Benzene etc. (J. Nuth, pers. comm.)



Variable Gas in Beta Pic

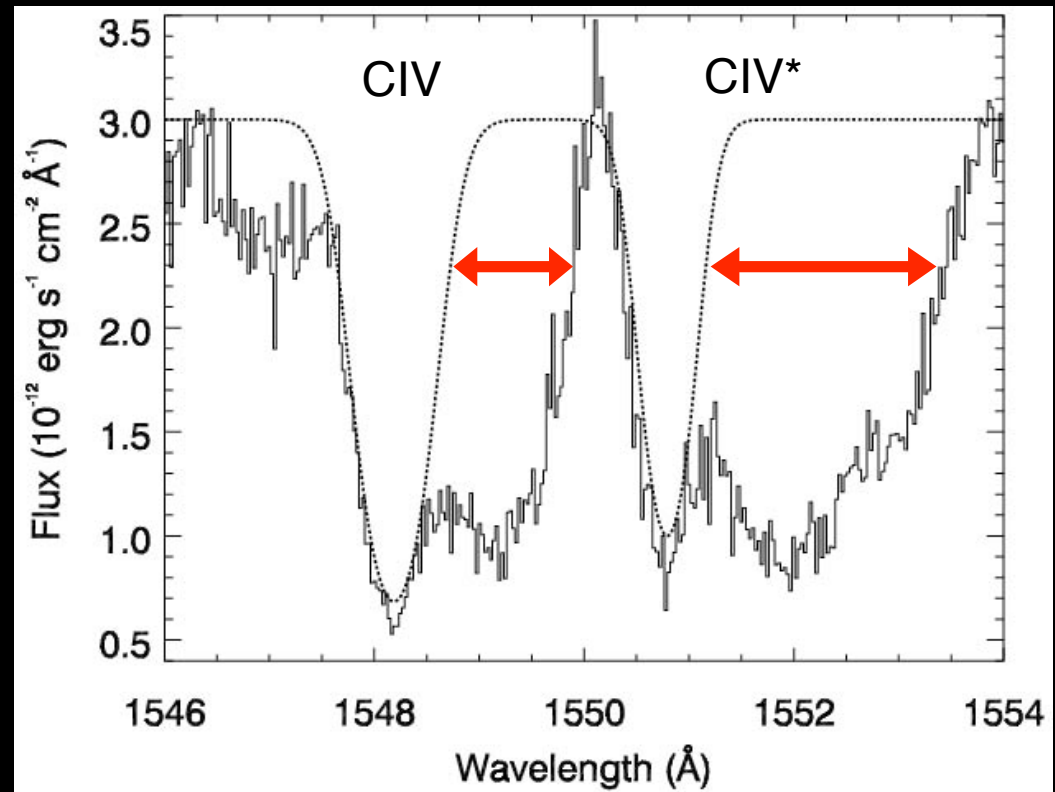
- Redshifted,
10s - 100s km/s
- Variability :
days to hours



Roberge et al. (2000)

Variable Gas in Beta Pic

- Redshifted,
10s - 100s km/s
- Variability :
days to hours

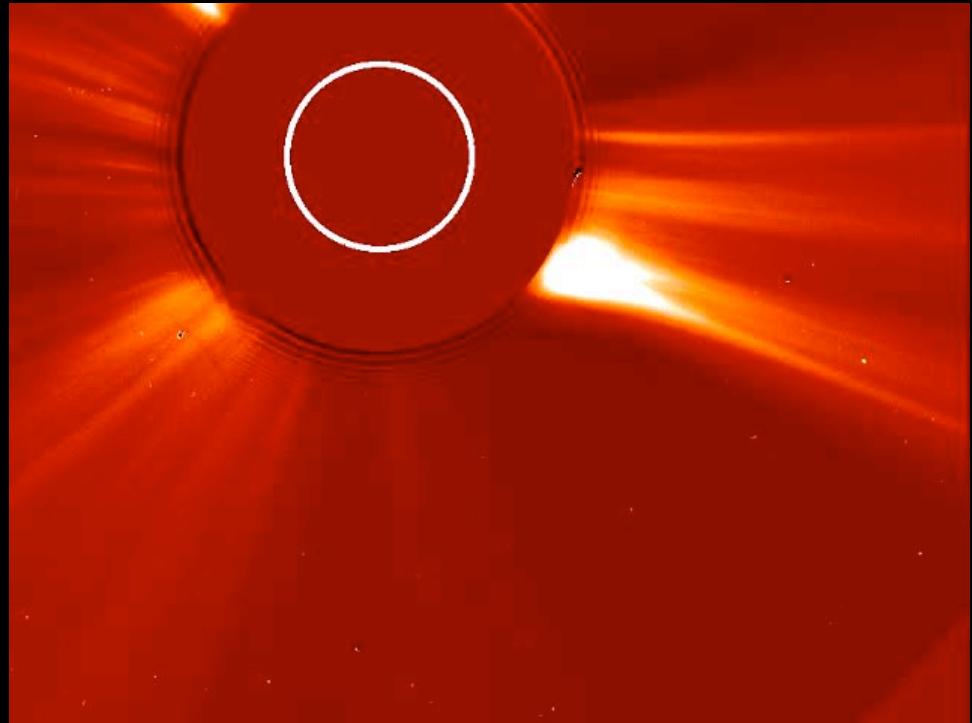


Bouret et al. (2002)

- Highly ionized species produced by
collisional ionization

Star-Grazing Comets

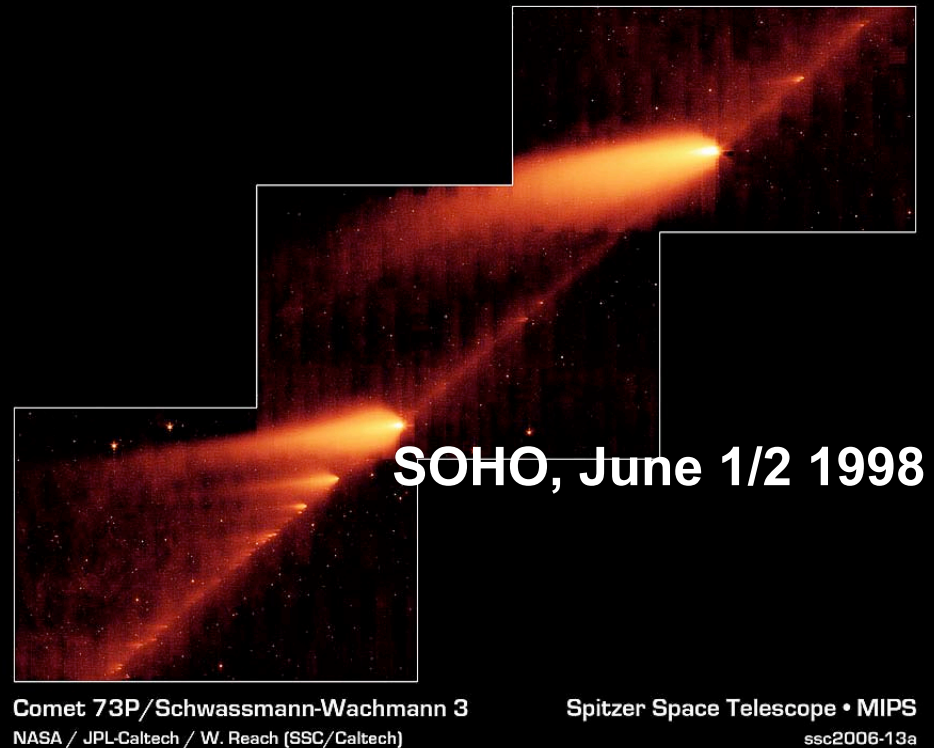
- Approach within few stellar radii
 - Collisionally ionized species formed in shock front
(Beust & Tagger 1993)
- Hundreds of star-grazers per year



SOHO, June 1/2 1998

Star-Grazing Comets

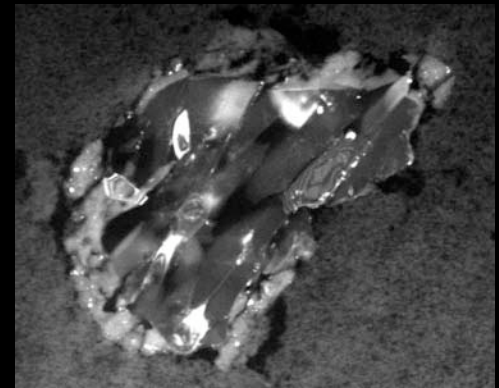
- Approach within few stellar radii
 - Collisionally ionized species formed in shock front
(Beust & Tagger 1993)
- Hundreds of star-grazers per year
- Families of comet fragments
(Ferlet et al. 1993)



Star-Grazing Comets ???

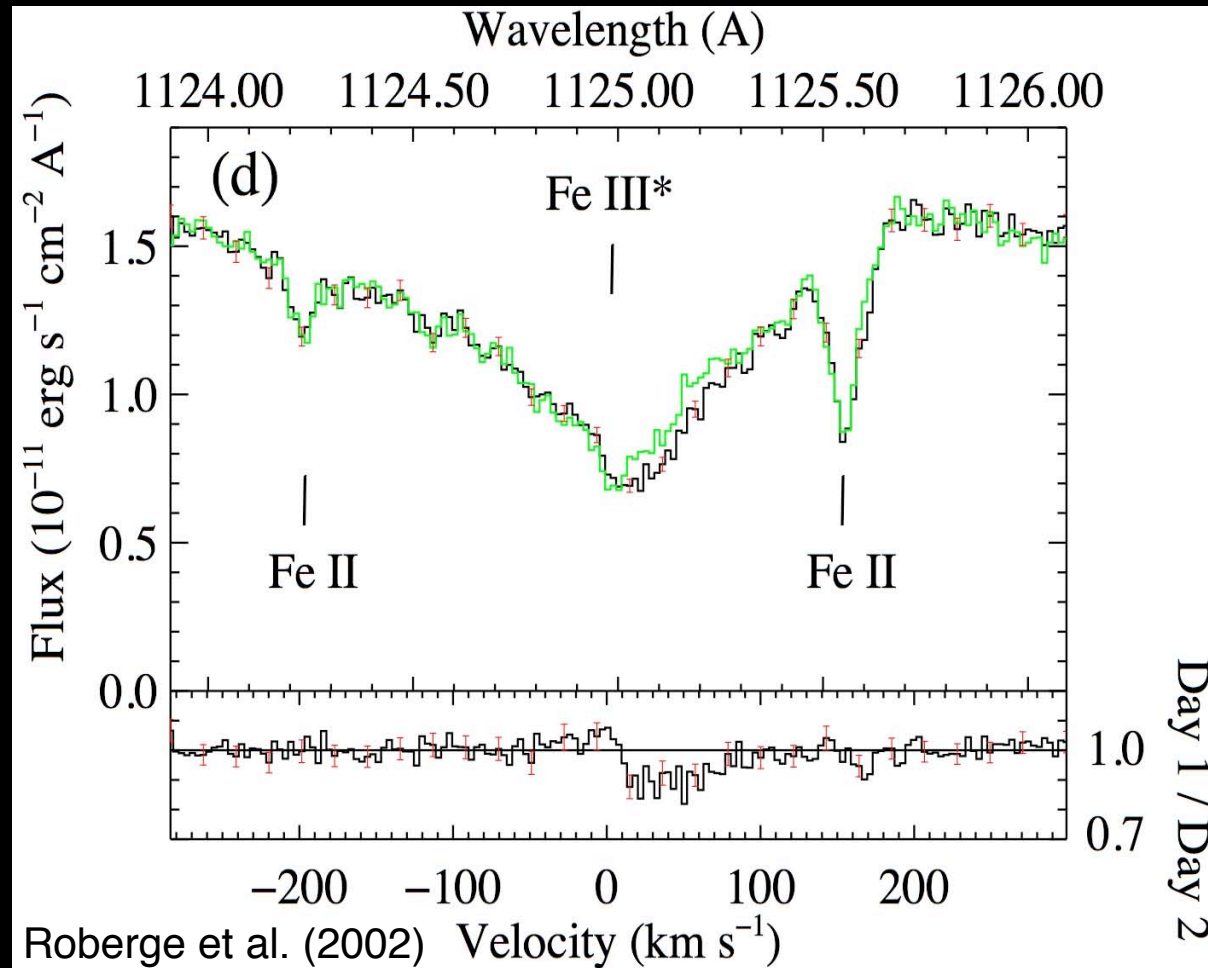
- Other claims of “ β Pic” phenomenon
 - e.g. UX Orionis (Grady et al. 2000)
 - Accretion of primordial gas (Natta et al. 2000)
 - Composition matters as well as dynamics
- 51 Ophiuchi
 - Variable infalling gas
(e.g. Grady & Silvis 1993)
 - Crystalline silicate emission ...
debris disk ?

Forsterite from comet Wild 2



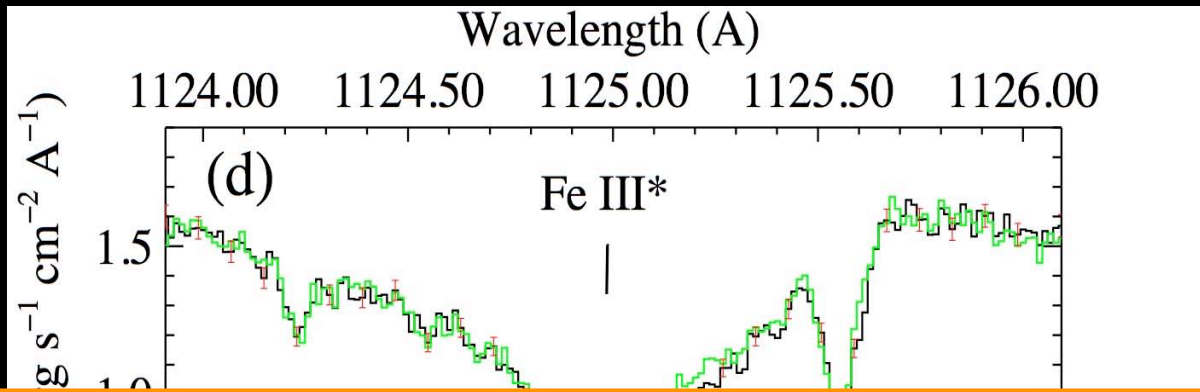
FUSE Spectra of 51 Oph

- Gas composition : volatile-depleted or iron-rich

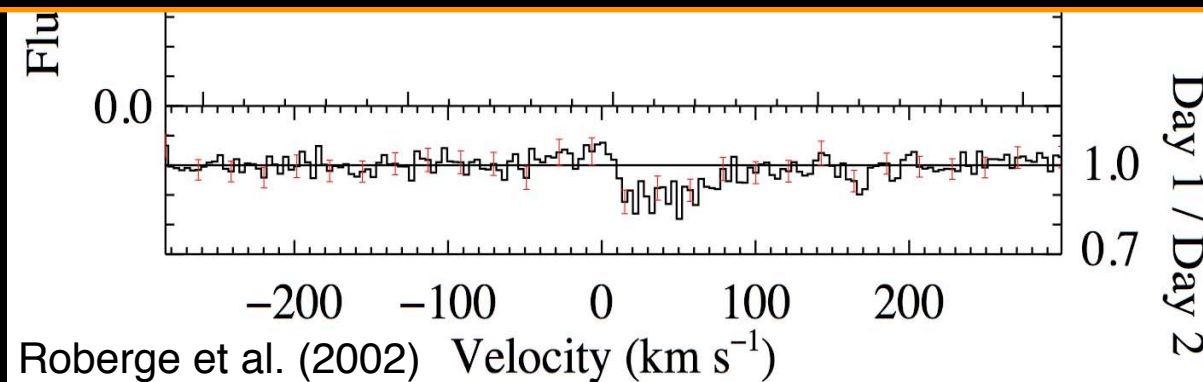


FUSE Spectra of 51 Oph

- Gas composition : volatile-depleted or iron-rich

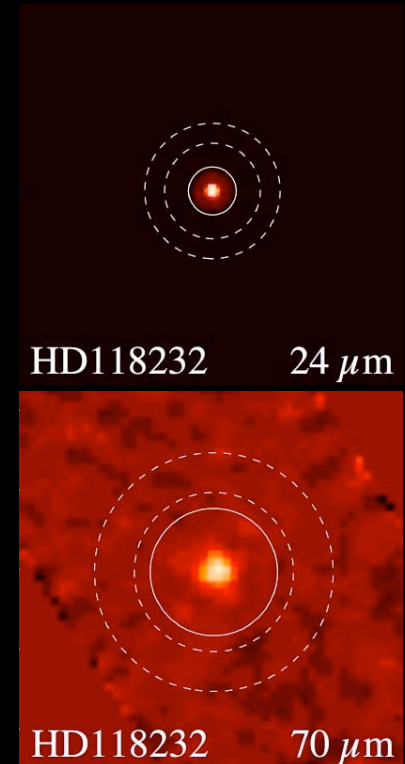
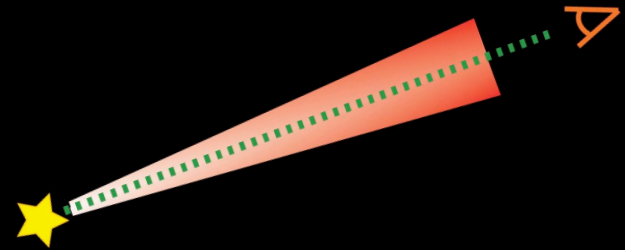


Recent destruction of a planet ?
van den Ancker et al. (2001)

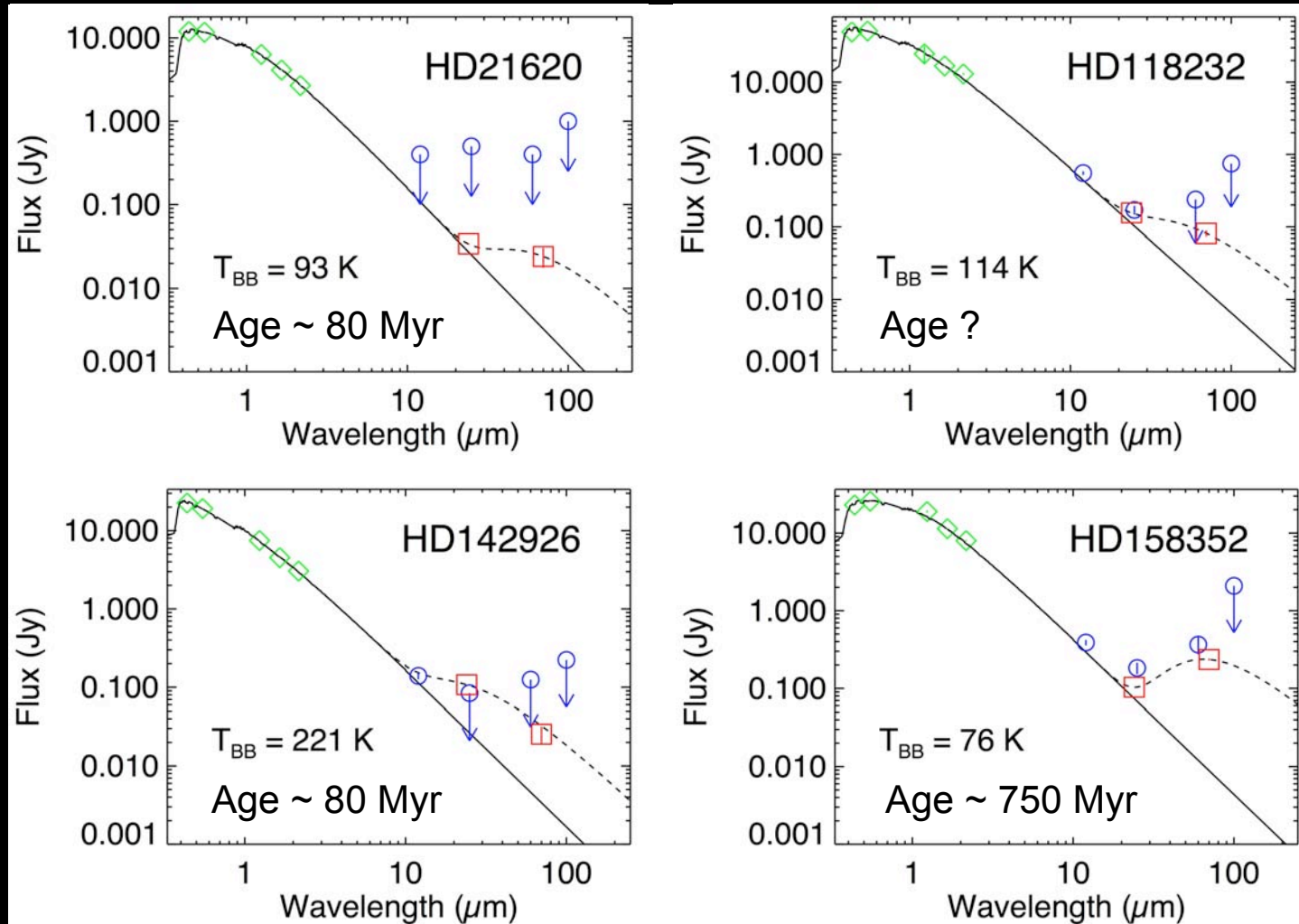


A Search for Disks w/ Gas

- Why do we know so little?
 - Cold gas, low abundances
 - Need edge-on disks
- Spitzer survey for circumstellar dust
 - Target stars have CS gas
 - Shell stars: evolved stars, classical Be stars, and protoplanetary/debris disks



New Disks with Gas & Dust

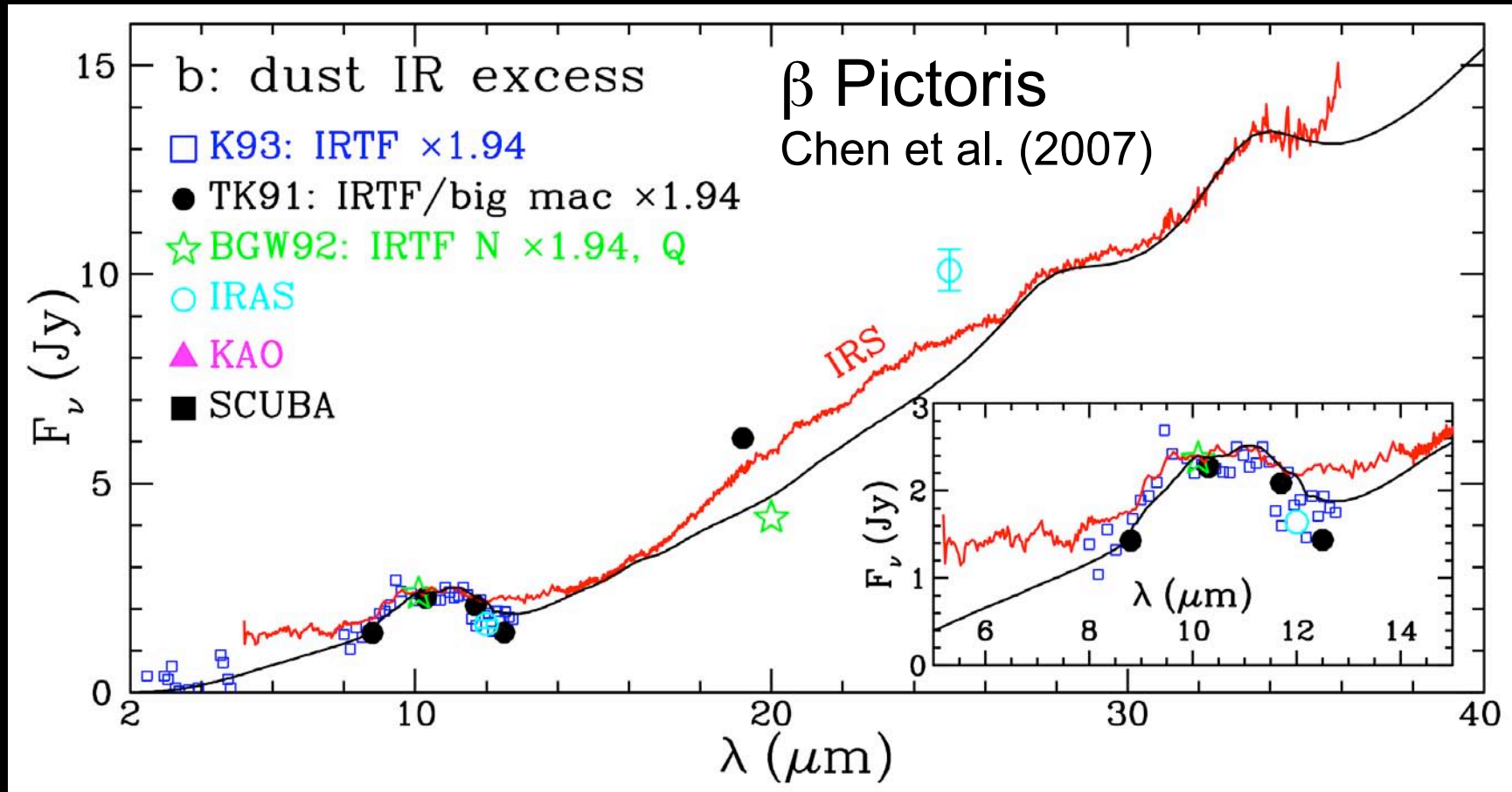


Roberge & Weinberger (2008)

Disks Among the Shell Stars

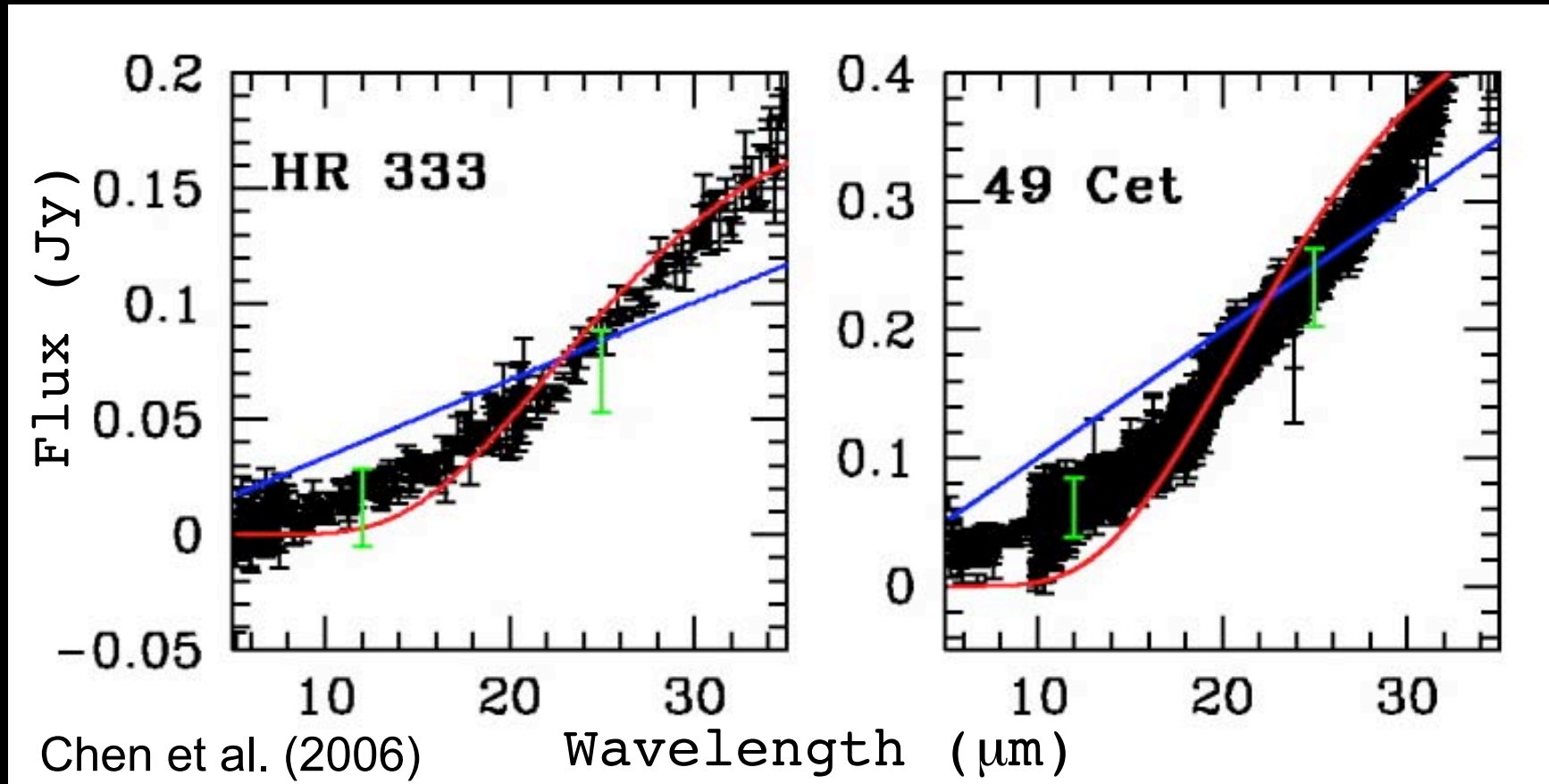
- Disk fraction $\geq 48\% \pm 14\%$
 - 7 known disks + 4 new disks out of 23
 - Could be as high as 65%
- May be higher than for normal MS A-stars
- Young stars as well as old ones in the shell star class
- Find dust disks by first looking for gas

Dust Composition from Mid-IR Spectra



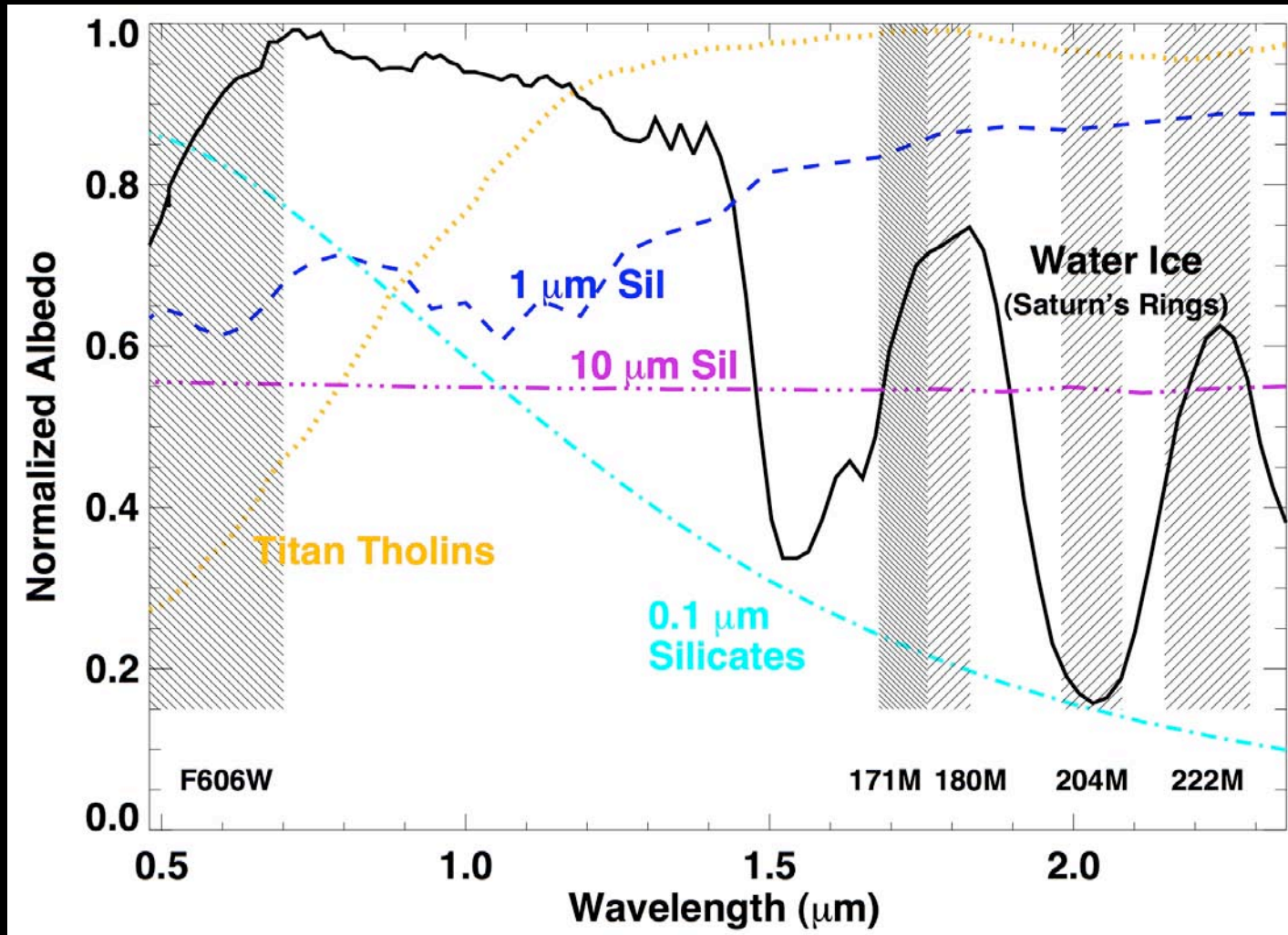
Small, warm amorphous & crystalline silicates

Dust Composition from Mid-IR Spectra



Cold grains, large grains \rightarrow no composition info.

Albedos of Grains



From A. Weinberger

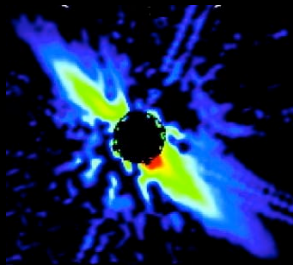
Dr. A. Roberge – “Gas and Dust in Debris Disks: Clues to the Late Stages of Planetary System Formation”

Scattered Light Colors

HD 32297

Blue

Schneider et al. (2005)



AU Mic

Blue

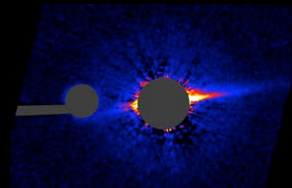
Krist et al. (2005)



HD 15115

Blue

Kalas et al. (2007)



HD 92945

Neutral

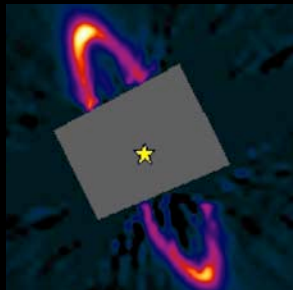
Golimowski et al., in prep.



HR 4796A

Red

Schneider et al., in prep.



Beta Pic

Red

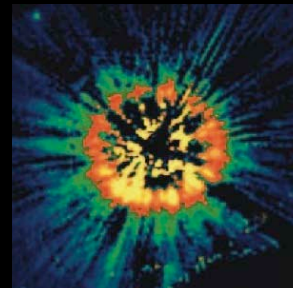
Golimowski et al. (2006)



HD 181327

Red

Schneider et al. (2006)



HD 107146

Red

Ardila et al. (2004)



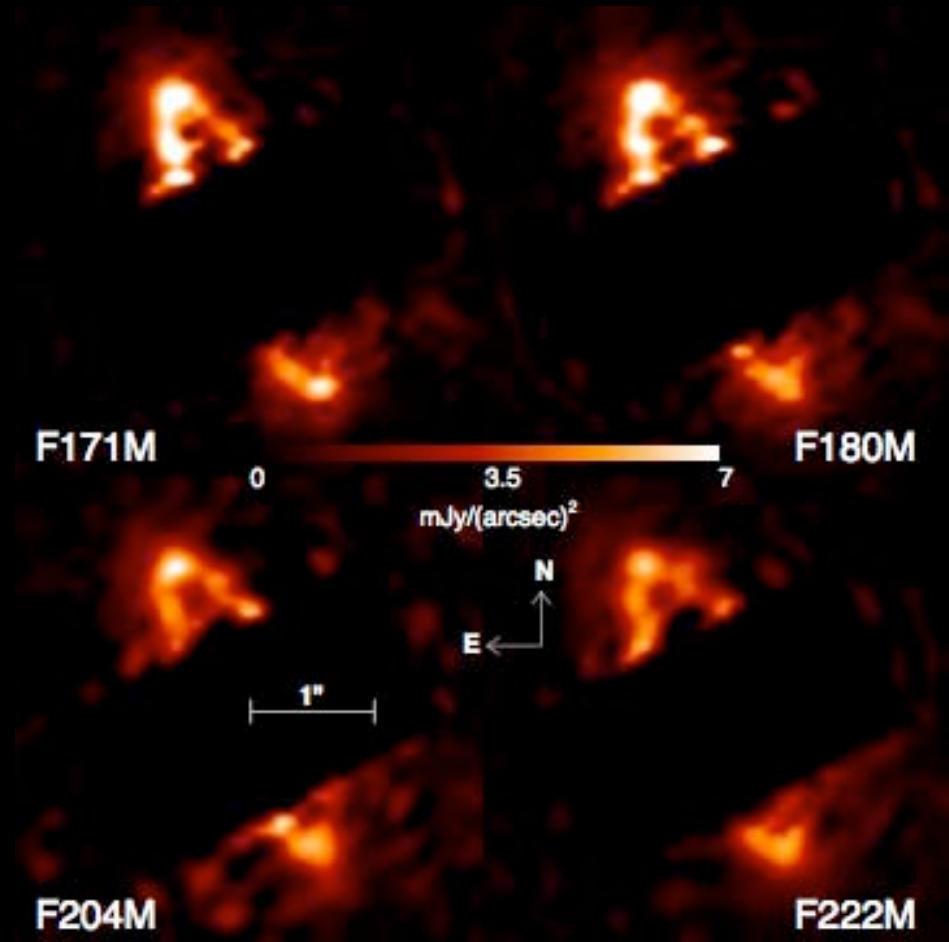
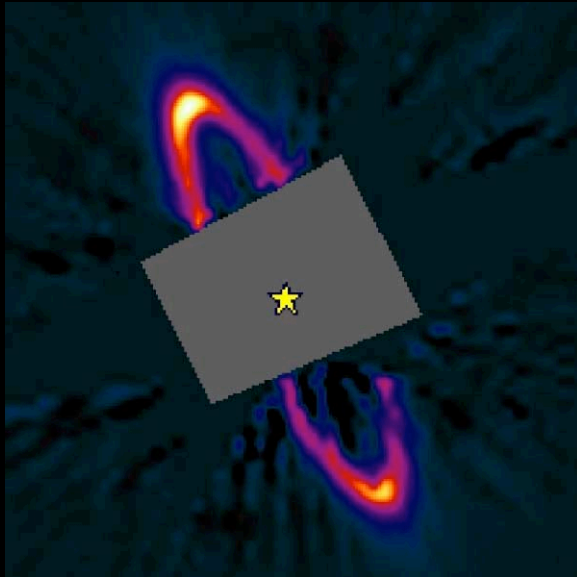
Organic Material in HR 4796A

NICMOS Images

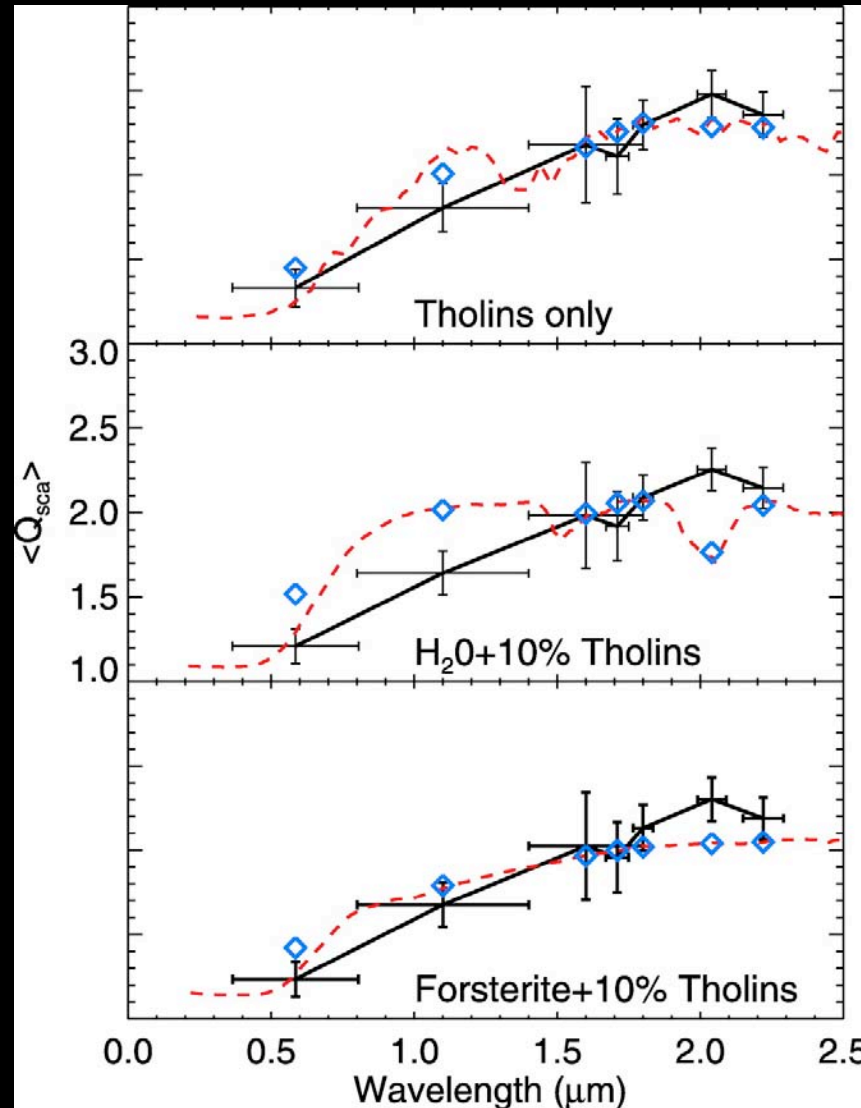
Debes, Weinberger, & Schneider (2008)

STIS Image

Schneider et al., in prep.



Organic Material in HR 4796A



Debes, Weinberger, & Schneider (2008)

Debris Disks as Exozodis

- Sun has a debris disk
 - Zodiacal dust comes from asteroids, comets
- Solar System : 1 zodi
- Beta Pic : ~ 10,000 zodis
- Exozodis are noise for planet imaging
 - More than 10 zodis is bad
 - Spitzer : $\geq 100 - 500$ zodis

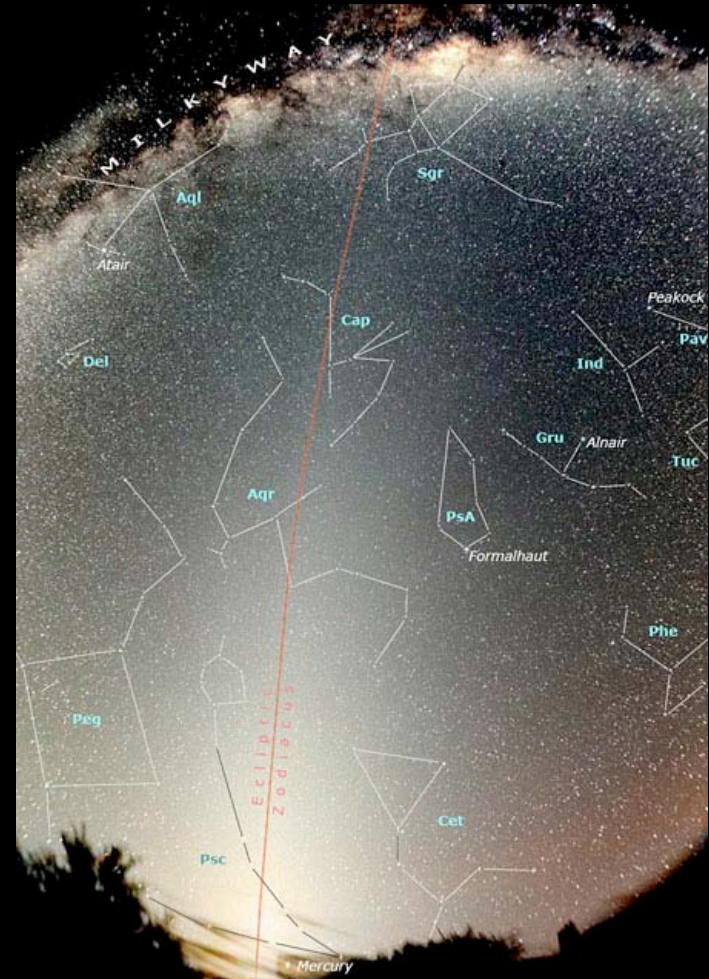
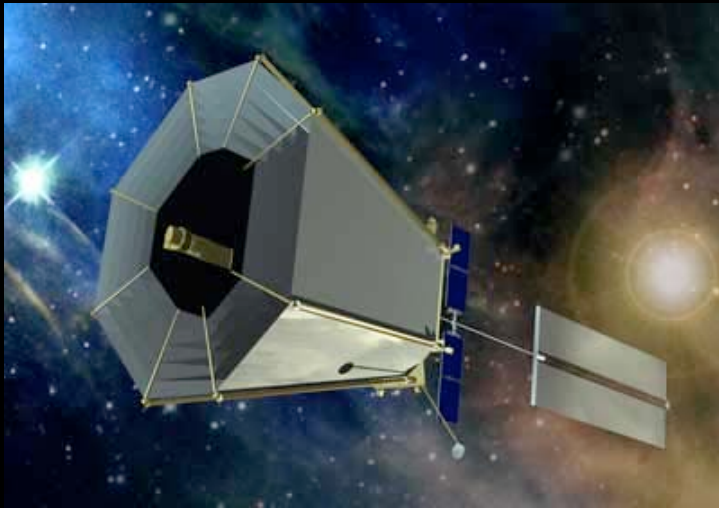


Image credit: Stefan Seip

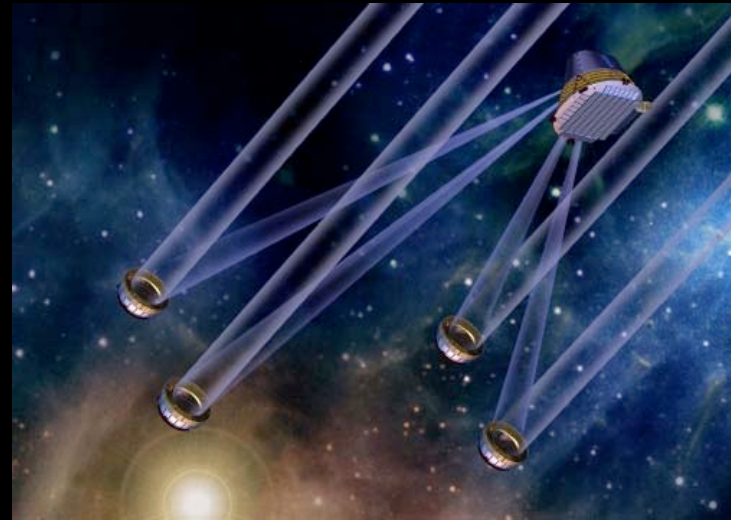
Imaging Terrestrial Planets

Goal: Earth at 1 AU, 10 pc distant

Requirement: 10^{10} fainter than star, 100 mas away



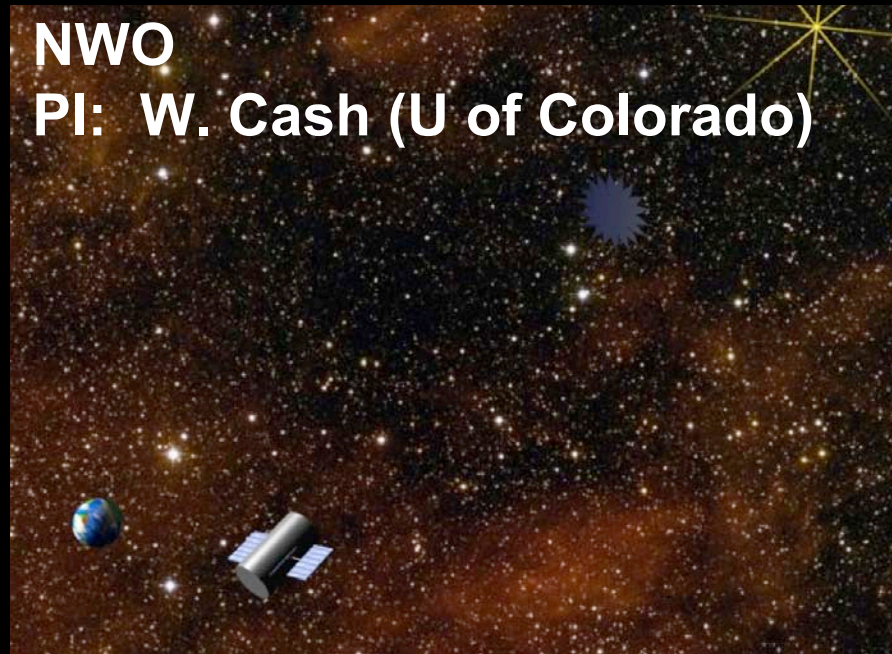
TPF-C
(optical)



TPF-I
(near-IR)

New Worlds Observer

- Occulting starshade
 - 72,000 km from telescope
 - “Simple” optical telescope
- General purpose observatory
 - 80% of time for other astronomy



Star Formation Observatory

PI: P. Scowen (ASU)

- Merged with XPC

PI: D. Spergel (Princeton)

Summary

1) Exciting upcoming studies of gas in protoplanetary disks

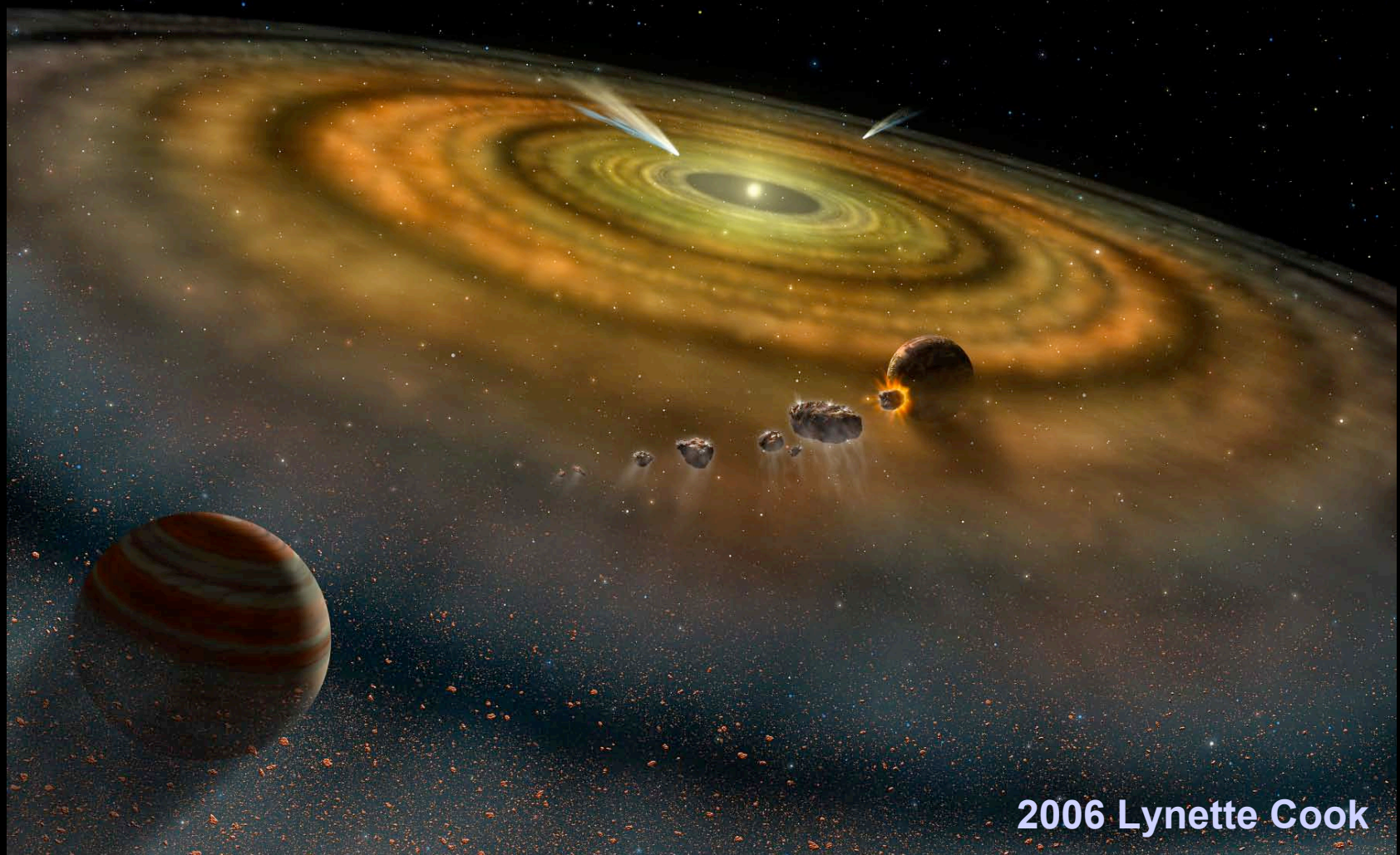


2) Debris gas & dust → composition of extrasolar planetesimals



3) Exozodi dust major concern for planet imaging





2006 Lynette Cook

Dr. A. Roberge – “Gas and Dust in Debris Disks: Clues to the Late Stages of Planetary System Formation”